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ARCTEC, Incorporated

ARCTIC TECHNOLOGY

Design, research and consulting in the fields of Arctic Marine Engineering, Ice Technology and Naval Architecture

ARCTEC, Incorporated

THE TRANSPORT AND BEHAVIOR OF OIL SPILLED IN AND UNDERSEA ICE

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PRESENTATION VIEW GRAPHS

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Prepared for

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THE TRANSPORT AND BEHAVIOR OF OIL SPILLED IN AND UNDER SEA ICE

CONTRACT NO, 03-78 -B01-62

RESEARCH UNIT 568

ARCTEC, INCORPORATED

COLUMBIA, MARYLAND

PURPOSE

TO SHOW THE FATE AND FINAL DESTINATION POINTS OF SPILLED OIL AND THEREBY ALLOWAN ASSESSMENT OF THE THREAT THE OIL POSES TO MARINE ORGANISMS,

QUESTIONS

GIVEN A NUMBER OF DIFFERENT OIL SPILL SCENARIOS:

- WHAT PERCENTAGE OF OIL SPILLED UNDER ICE REMAINS THERE AND HOW LONG?
- WHAT IS THE NATURE OF OIL MOVEMENT AND DISPERSION IN AND UNDER THE ICE, INCLUDING THE HORIZONTAL TRANSPORT UNDER ICE OF VARIOUS ROUGHNESSES DUE TO THE ACTION OF OCEAN CURRENTS, AND THE VERTICAL TRANSPORT THROUGH THE BRINE CHANNELS OF FIRST YEAR AND MULTI-YEAR ICE?
- HOW DOES OIL OF DIFFERENT VISCOSITIES RESPOND TO THESE VARIOUS DISPERSION PROCESSES?
- WHAT IS THE BULK TRANSPORT OF SPILLED OIL BY SEA ICE OF DIFFERENT SURFACE COVERAGE CONCENTRATIONS?
- HOW MUCH OF THE SPILLED OIL GETS INCORPORATED IN PRESSURE RIDGES?

OVERALL PROGRAM TASKS

TASK 1- ARCTEC, INCORPORATED (RESEARCH UNIT 568)

TO DETERMINE BY FIELD AND LABORATORY EXPERIMENTS THE PHYSICAL PROCESSES BY WHICH SPILLED OIL GETS INCORPORATED IN AND TRANSPORTED UNDER SEA ICE.

TASK 2- FLOW RESEARCH COMPANY (RESEARCH UNIT 567)

TO DETERMINE BY NUMERICAL MODELING THE ICE VELOCITY FIELD AND THE DEFORMATION OF SEA ICE ON THE CONTINENTAL SHELVES OF THE BEAUFORT AND CHUKCHI SEAS SO THAT OIL SPILL TRAJECTORIES CAN BE DEDUCED FOR DIFFERENT ICE CONDITIONS UNDER MEAN CLIMATOLOGICAL CONDITIONS AND EXTREME EVENTS, INCLUDING A MAJOR SEA ICE OUTBREAK FROM THE CHUKCHI SEA TO THE BERING SEA.

TASK 3 - FLOW RESEARCH COMPANY

TO DETERMINE BY COMBINING THE ABOVE WORK THE SEQUENCE OF EVENTS, LIKELY TRAJECTORIES, AND DESTINATION POINTS FOR OIL SPILLED IN SEVERAL HYPOTHETICAL SCENARIOS IN THE PRUDHOE BAY AREA.

SUBTASKS OF TASK 1

SUBTASK 1.1 - TO DETERMINE HOW AND AT WHAT RATES OIL MOVES UPWARD THROUGH MULTI-YEAR ICE TO THE SURFACE,

SUBTASK 1.2 - TO DETERMINE HOW AND AT WHAT RATES OIL GETS INCORPORATED INTO PRESSURE RIDGES FORMED FROM ICE OF VARIOUS THICKNESSES,

SUBTASK 1.3 - TO DETERMINE HOW OIL OF DIFFERENTVIS-COSITIES SPREADS AND IS MOVED BY OCEAN CURRENTS UNDER SEA ICE WITH DIFFERENT UNDERSIDE ROUGHNESS CHARACTERISTICS!

HORIZONTAL TRANSPORT UNDER ICE

PROBLEM STATED IN TERMS OF:

- SMOOTH ICE
- UNDULATING ICE
- ROUGH ICE
- BROKEN ICE FIELDS
- RAFTED ICE
- HUMMOCKS
- UNCONSOLIDATED PRESSURE RIDGES
- CONSOLIDATED PRESSURE RIDGES
- LEADS
- ICE EDGES

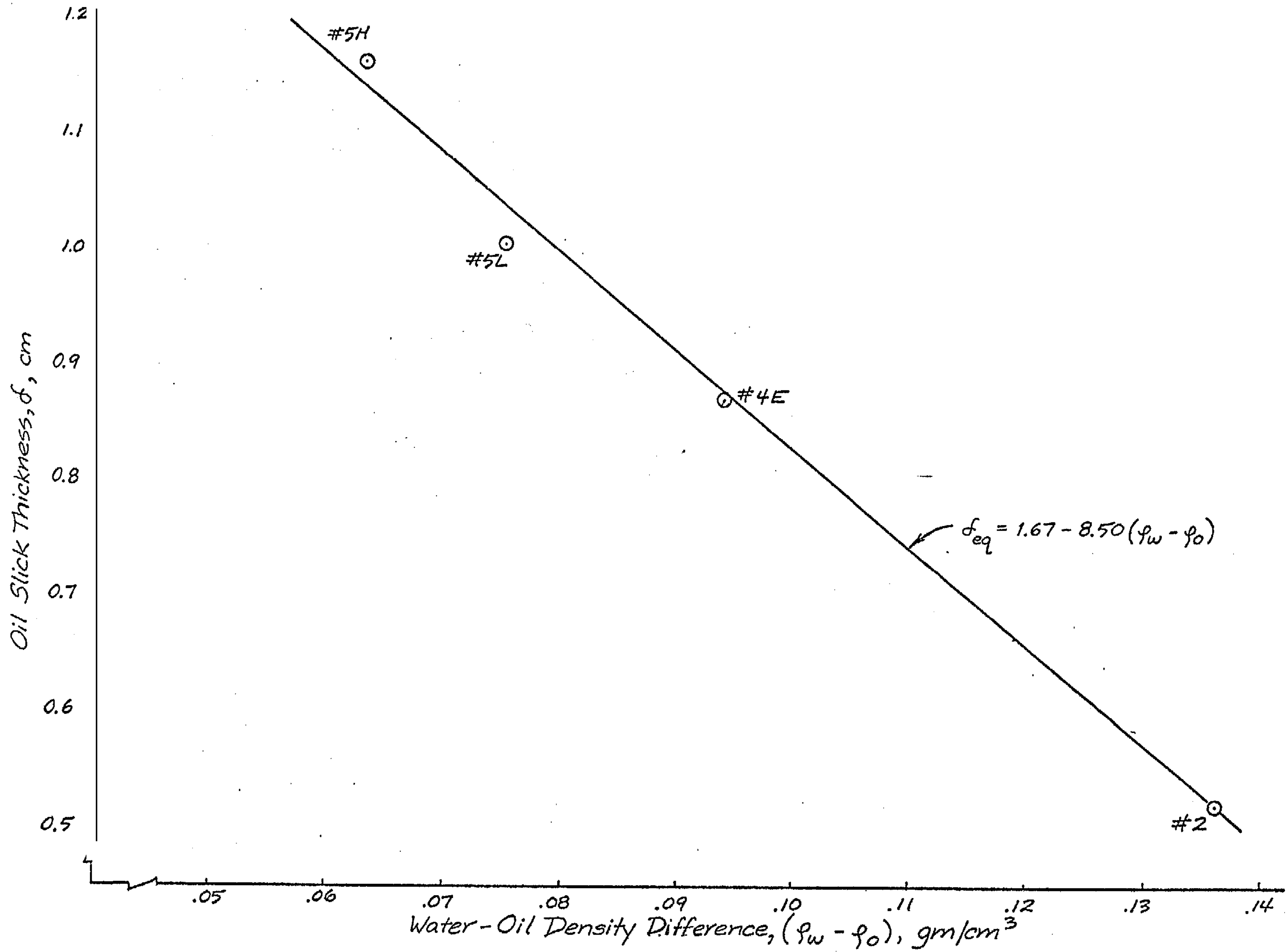
PROBLEM ADDRESSED IN TERMS OF:

- SMOOTH ICE
- SMALL ROUGHNESS ELEMENTS
- CONSOLIDATED LARGE ROUGHNESS ELEMENTS
- UNCONSOLIDATED LARGE ROUGHNESS ELEMENTS
- WAKES
- CAVITIES

SLICK THICKNESS

LINEAR EMPIRICAL RELATIONSHIP BETWEEN STATIC EQUILIBRIUM OIL SLICK THICKNESS BENEATH SMOOTH ICE AND THE WATER - OIL DENSITY DIFFERENCE:

$$\delta = 1.67 - 8.50 (\rho_w - \rho_o)$$



Empirical Relationship Between Slick Thickness and Density Difference

SMOOTH ICE

A BASE CASE FOR THE LABORATORY STUDIES, NOT A FIELD SITUATION

- THRESHOI-.D VELOCITY

EMPIRICAL RELATIONSHIP BETWEEN THRESHOLD VELOCITY IN CM/SEC AND OIL VISCOSITY IN POISE WAS FOUND TO BE:

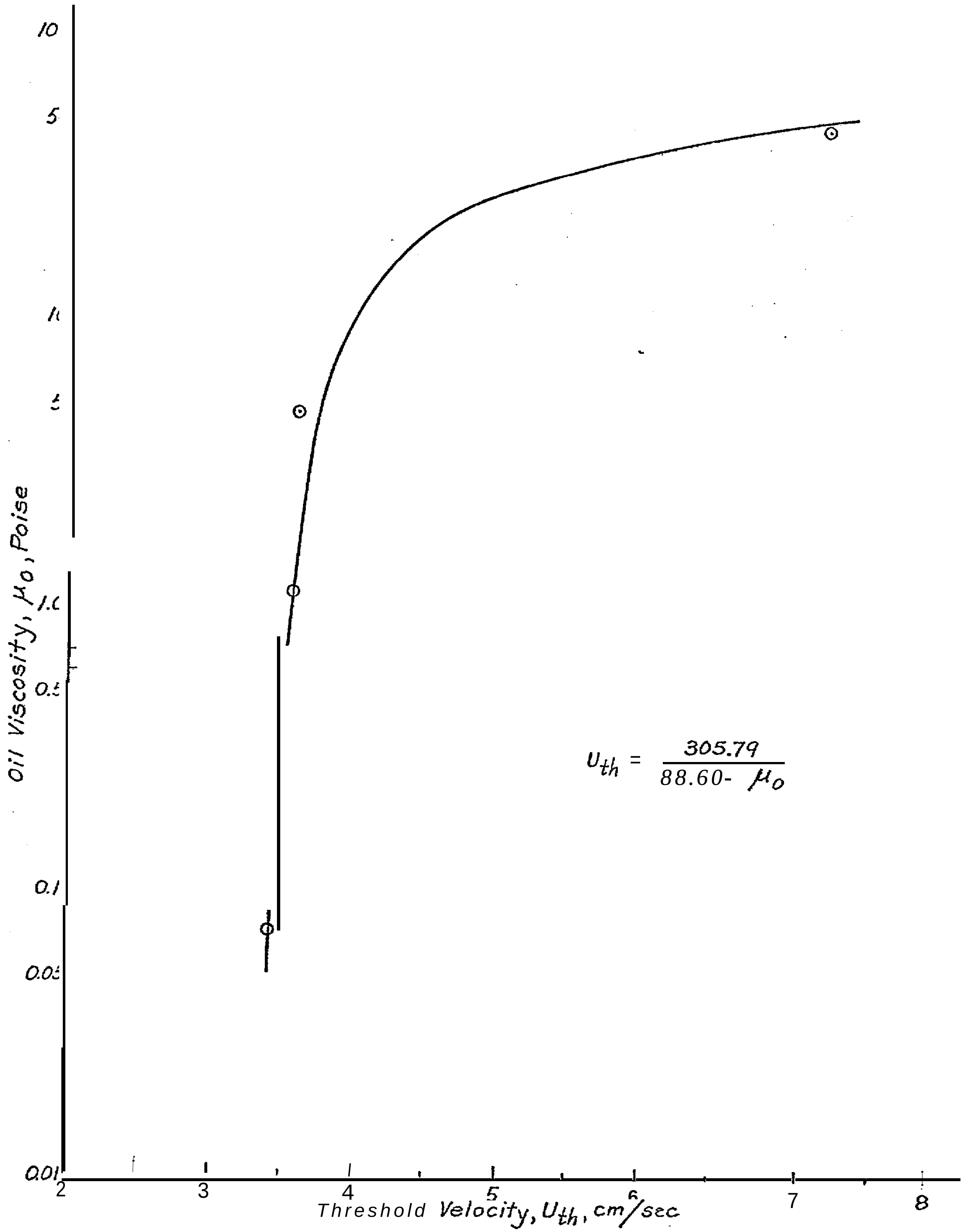
$$U_{th} = \frac{305.79}{88.68 - \mu_o}$$

- SLICK VELOCITY

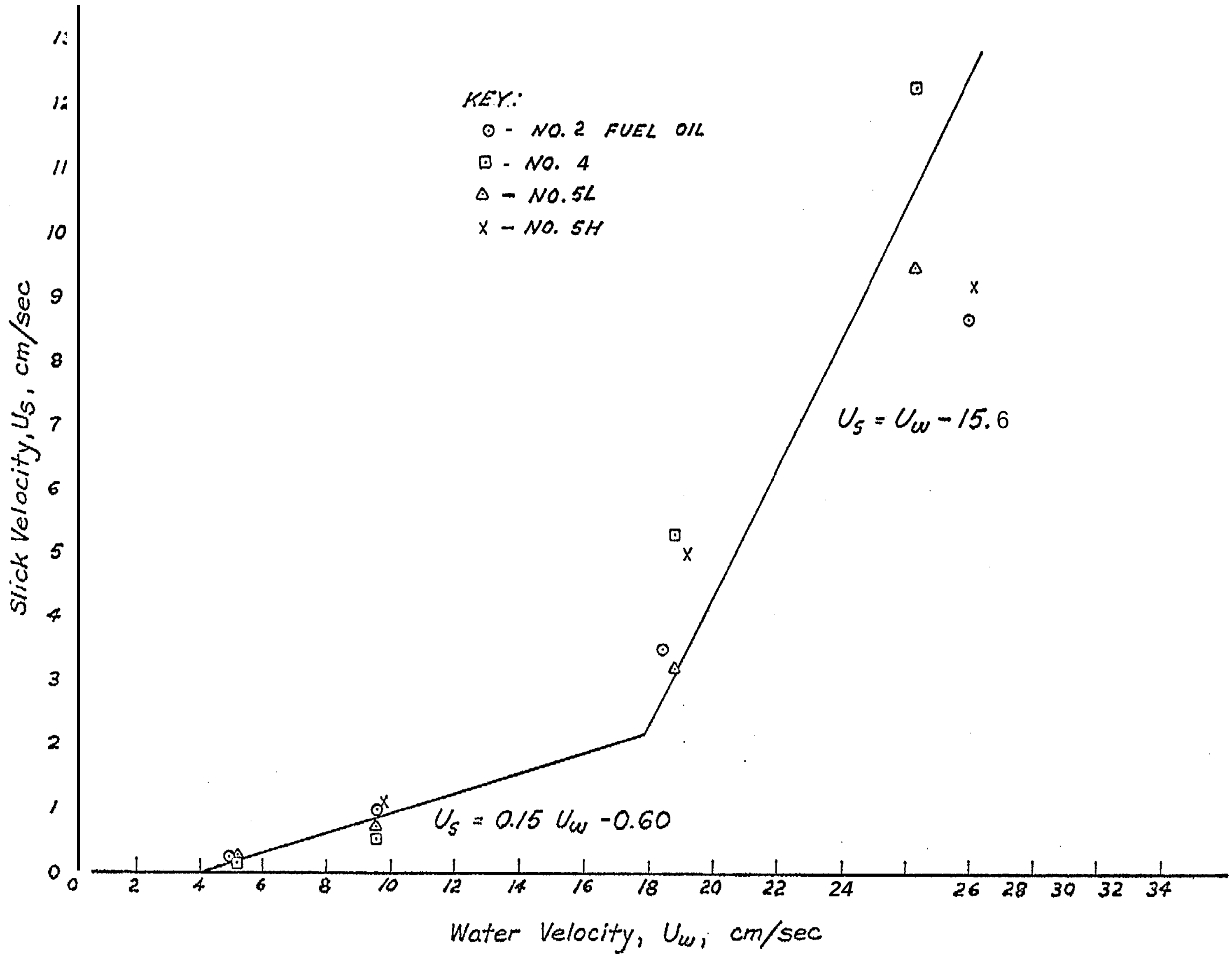
TWO STEP LINEAR RELATIONSHIP BETWEEN SLICK VELOCITY AND CURRENT VELOCITY APPROXIMATED FOR ALL OILS TESTED BY:

$$U_s = 0.15\ U_w - 0.60 \qquad \text{for } U_w < 18 \text{ cm/sec}$$

$$U_s = U_w - 15.6 \qquad \text{for } U_w > 18 \text{ cm/sec}$$



Plot of Oil Slick Threshold Velocity versus Oil Viscosity for Oil Beneath Smooth Ice



Plot of Oil Slick Velocity versus Current Velocity for the Horizontal Transport of Oil Beneath Smooth Ice Cover

SMALL ROUGHNESS

- ROUGHNESS AMPLITUDE LESS THAN EQUILIBRIUM SLICK THICKNESS,
- EVEN A SLIGHT AMOUNT OF UNDER-ICE ROUGHNESS CAUSED A SUBSTANTIAL INCREASE IN THE THRESHOLD VELOCITY OF AN UNDER-ICE OIL SLICK:

SLICK THRESHOLD VELOCITY, CM/SEC

	SMOOTH	$\frac{1}{4}$ MM AMPL. ON 4 CM SPACING	$\frac{1}{4}$ CM AMPL. ON 4 CM SPACING
NO. 4 OIL	4	12	22
NO. 5H OIL	7	16	25

- A GENERALIZED SLICK VELOCITY RELATION DEVELOPED FOR SMOOTH ICE AND SMALL ROUGHNESS ICE IS:

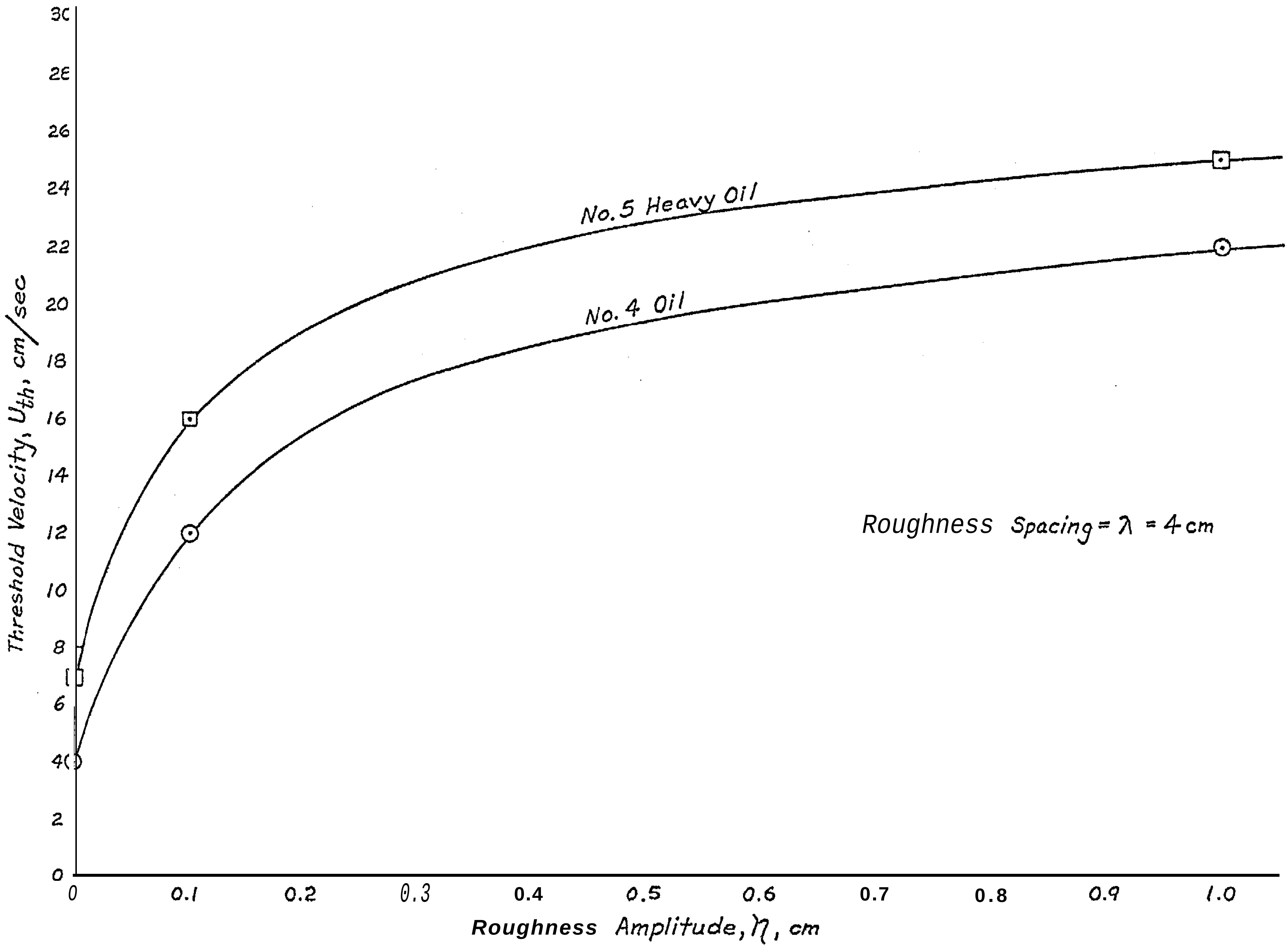
$$\left(1 - \frac{U_s}{U_w}\right)^2 = \frac{K}{0.115\ F_\delta^{\,2} + 1.105}$$

WHERE:

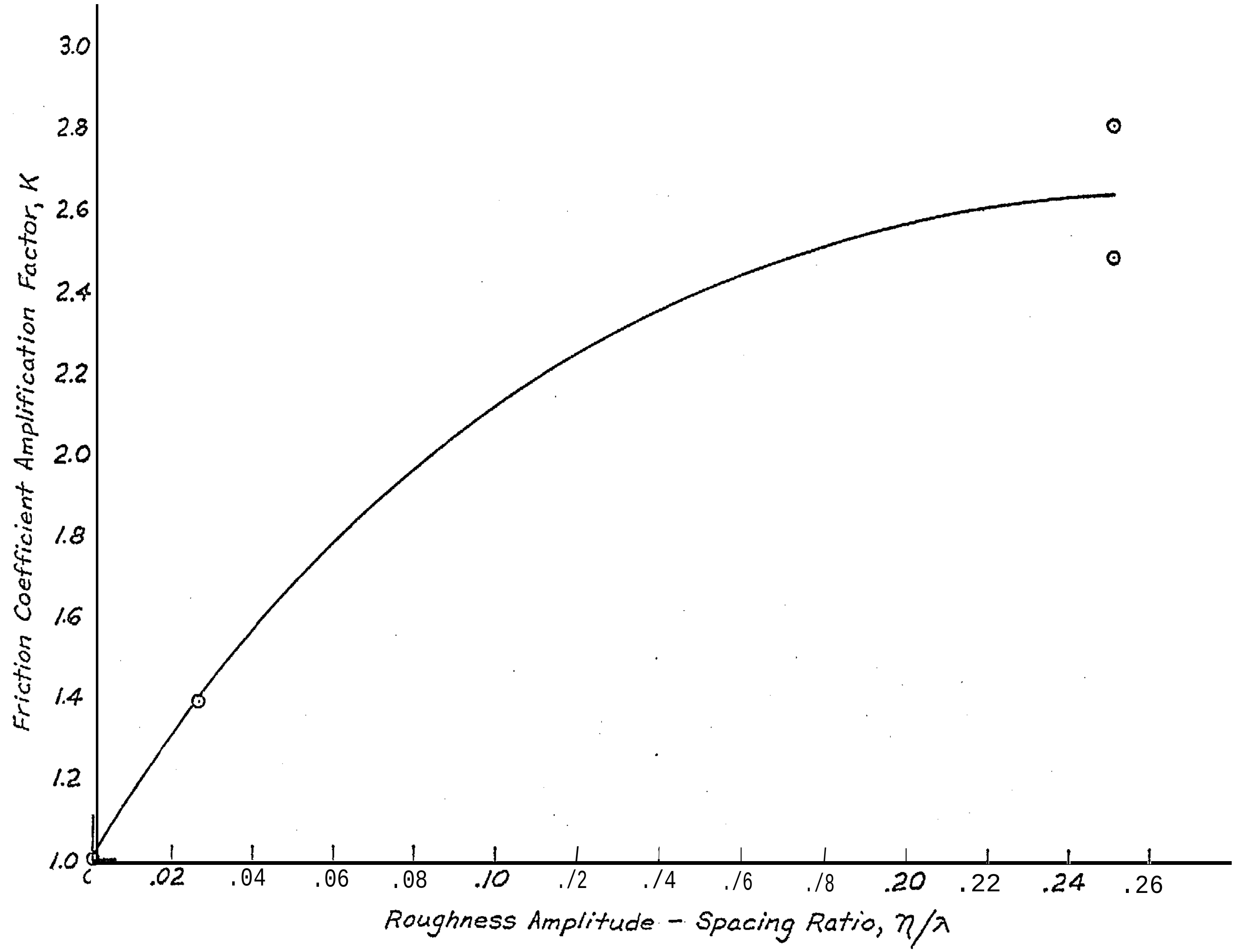
$$F_\delta = \frac{U_w}{\sqrt{\Delta g \delta}}$$

$$\Delta = \frac{\rho_w - \rho_o}{\rho_w}$$

K = AMPLIFICATION FACTOR FOR THE OIL-ICE FRICTION FACTOR (EQUALS 1 FOR SMOOTH ICE, >1 FOR SMALL ROUGHNESS ICE)



Variation of Under Ice Slick Threshold Velocity with Ice Surface Roughness



Projection of Friction Coefficient Amplification Factor as a Function of the Roughness Amplitude to Spacing Ratio

LARGE ROUGHNESS

- ROUGHNESS AMPLITUDE GREATER THAN EQUILIBRIUM SLICK THICKNESS

FRONTAL TRAPPING OF OIL

- POTENTIAL OF TOTALLY RESTRAINING AN ADVANCING SLICK UP TO SOME CRITICAL VALUE OF CURRENT VELOCITY,

- CONFINED SLICK HAS THREE DISTINCT REGIONS:
  1. HEAD REGION
  2. NECK REGION
  3. TAIL REGION

- TWO CONTAINMENT FAILURE, OR RELEASE, MECHANISMS:
  1. TAIL LEAKAGE DUE TO FILLING BEYOND EQUILIBRIUM VOLUME DICTATED BY THE FLOW CONDITIONS:

$$V' = \frac{\left(\eta + \frac{U_w^2}{4\Delta g}\right)}{2} \left(\frac{4\Delta g}{f_s U_w^2}\right) \left(\eta^2 - \frac{U_w^2}{4\Delta g}\right)$$

WHERE :

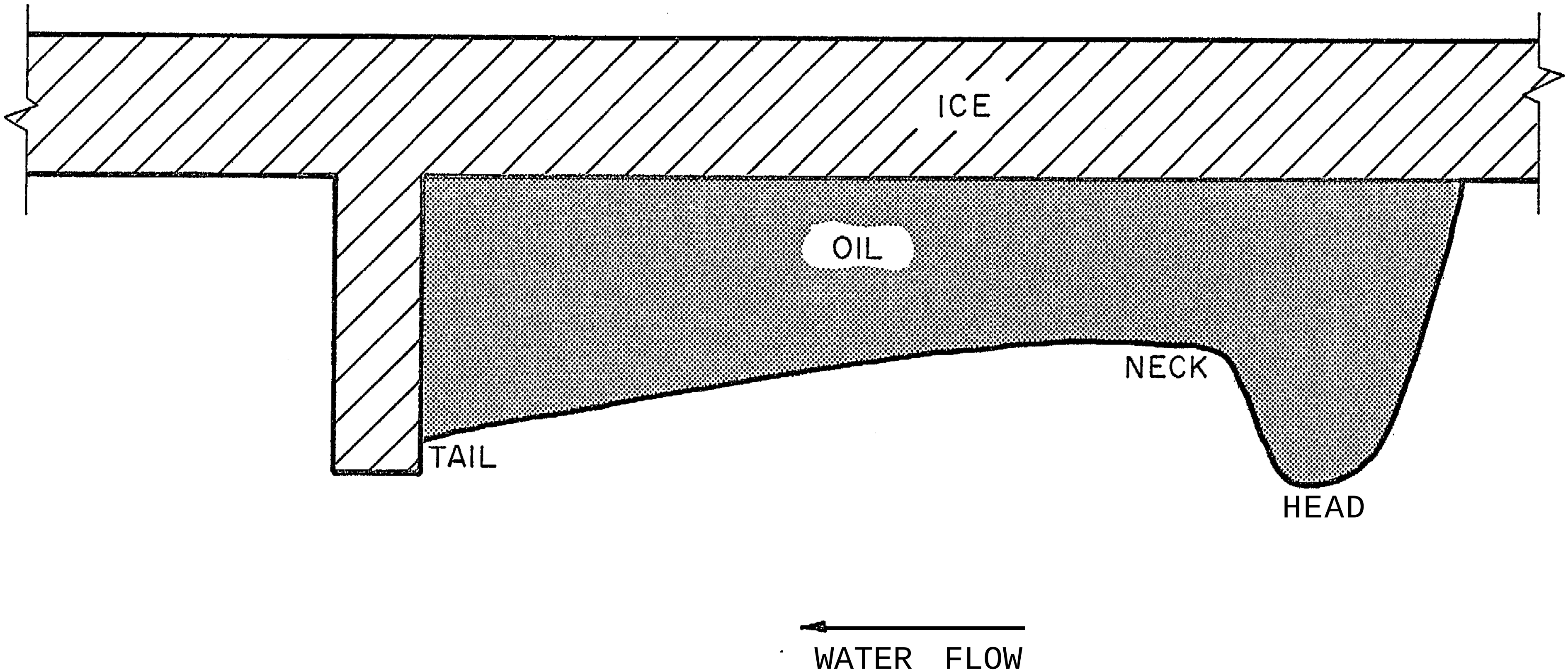
V' = VOLUME CONTAINED PER UNIT WIDTH FOR THE DEEP WATER CASE $\frac{\delta}{D} < 0.01$

f_s = SLICK-WATER INTERFACIAL FRICTION FACTOR = 0.03

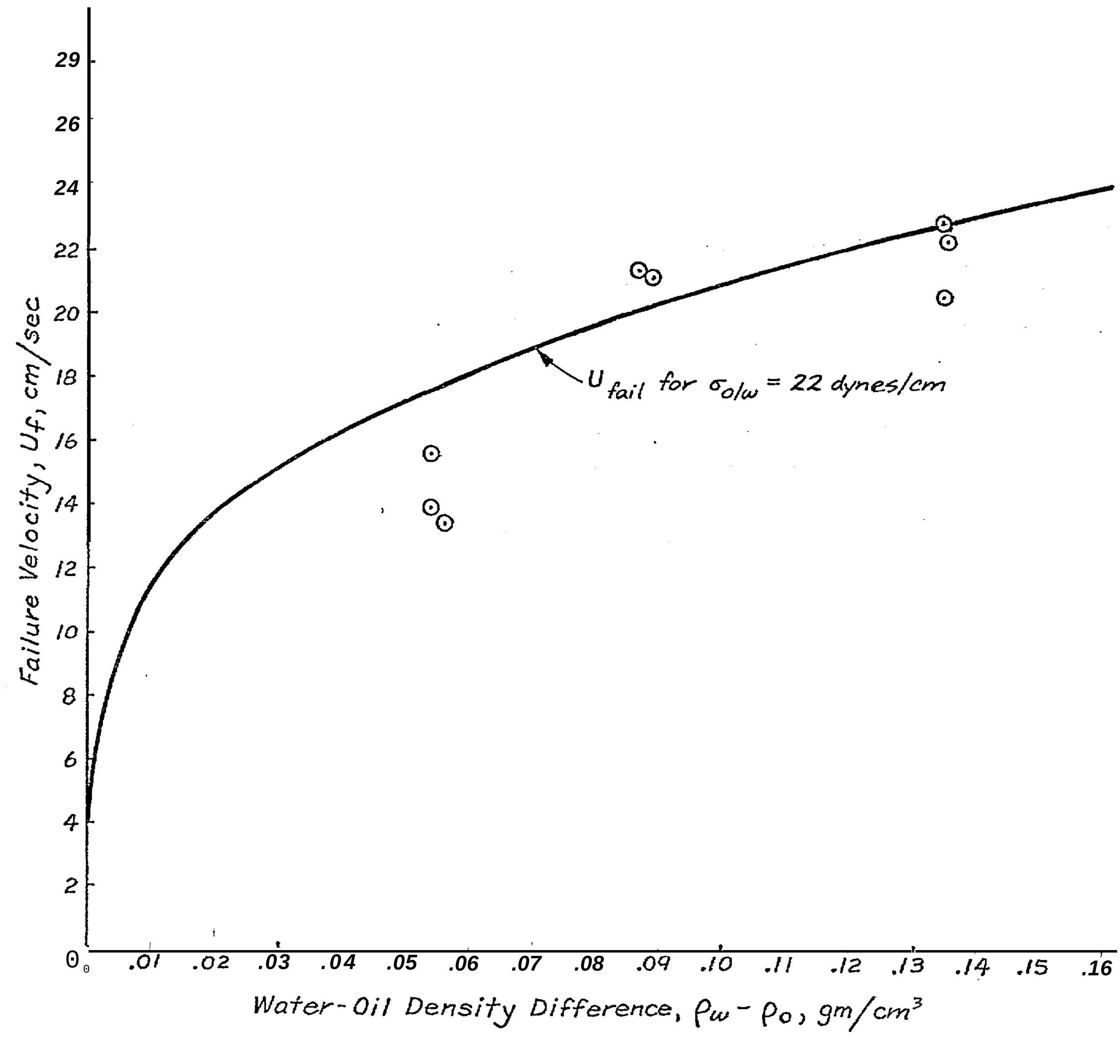
η = ROUGHNESS HEIGHT

  2. TOTAL FLUSHING FROM THE HEAD REGION AT A CRITICAL CURRENT VELOCITY FOR AN OIL OF GIVEN DENSITY IN DEEP WATER:

$$U_f = 1.5\left[2\left(\frac{\rho_o+\rho_w}{\rho_o\ \rho_w}\right) \left(\sigma_{o/w}\ g\ (\rho_w-\rho_o)\right)^{1/2}\right]^{1/2}$$



Sketch of the Shape Taken by a Slick Confined Behind a Large Roughness Element or Obstruction



Relationship Between Failure Velocity and Water-Oil Density Difference for Containment of Oil Upstream of an Obstruction

LARGE ROUGHNESS
WAKE TRAPPING OF OIL

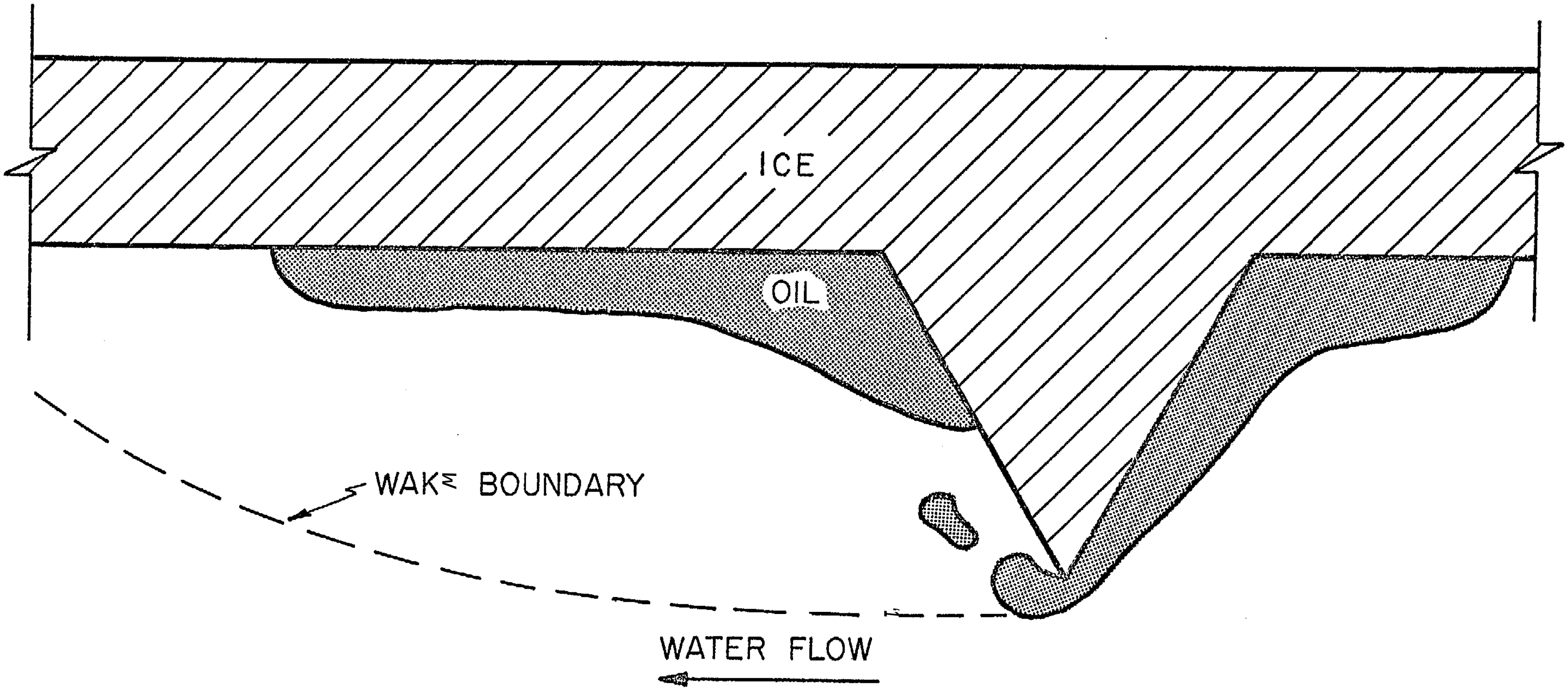
- BELOW FRONTAL FLUSHING VELOCITY, SMALL CONTAINMENT CAPACITY AT EQUILIBRIUM SLICK THICKNESS OVER ABOUT 70% OF WAKE LENGTH, CONTAINED VOLUME PER UNIT WIDTH FOR ROUGHNESS HEIGHT n IS GIVEN BY:

$$V' = 6 \; C_D \; n \; \delta_{eq}$$

  WHERE

$$C_D = 1.98 \text{ FOR FLAT FENCE}$$
$$= 1.55 \text{ FOR TRIANGULAR SHAPE,}$$

- ABOVE FRONTAL FLUSHING VELOCITY, OIL CONTAINED IN A WAKE REGION CLEARS IN A TIME PERIOD OF MINUTES TO HOURS, THEREFORE, LONG TERM CONTAINMENT CAPACITY IS NIL,



Sketch of Oil Leakage From Upstream of a Large Roughness Element to the Wake Region Behind the Element

LARGE ROUGHHESS
UNCONSOLIDATED (POROUS) . OBSTRUCTIONS

- NO FRONTAL TRAPPING - MIGRATION INTO PORES AND UP ON THE ICE SURFACE OR THROUGH THE OBSTRUCTION TO THE DOWNSTREAM SIDE,
- BEHAVIOR IN WAKE REGION QUALITATIVELY SIMILAR TO THE CONSOLIDATED OBSTRUCTION CASE.

LARGE ROUGHNESS
CAVITY TRAPPING OF OIL

- OIL CONTAINED IN A CAVITY OF LENGTH λ IS CHARACTERIZED BY TWO ZONES, A VORTEX ZONE AND A SHEAR ZONE.

- THE EXISTENCE OF A CAVITY, AS OPPOSED TO SEPARATE FRONTAL AND WAKE TRAPPING, REQUIRES THAT:
  1. CAVITY DEPTH BE GREATER THAN THE VORTEX ZONE OFFSET,
  2. CAVITY LENGTH BE LESS THAN THE CALCULATED LENGTH OF THE VORTEX ZONE PLUS THE SHEAR ZONE,

- FOR A CAVITY, CONTAINMENT IN THE VORTEX ZONE IS CONTROLLED BY ITS LENGTH, GIVEN EMPIRICALLY BY:

$$\ell = 4\ U_w$$

AND AN OFFSET CAUSED BY VORTEX SHEDDING FROM THE TIP OF THE UPSTREAM ROUGHNESS ELEMENT GIVEN BY:

$$\varepsilon = \frac{U_w^{\ 2}}{1.86\ Ag}$$

YIELDING A CONTAINED VOLUME PER UNIT WIDTH WHICH IS A FUNCTION OF VELOCITY IN THE VORTEX ZONE OF:

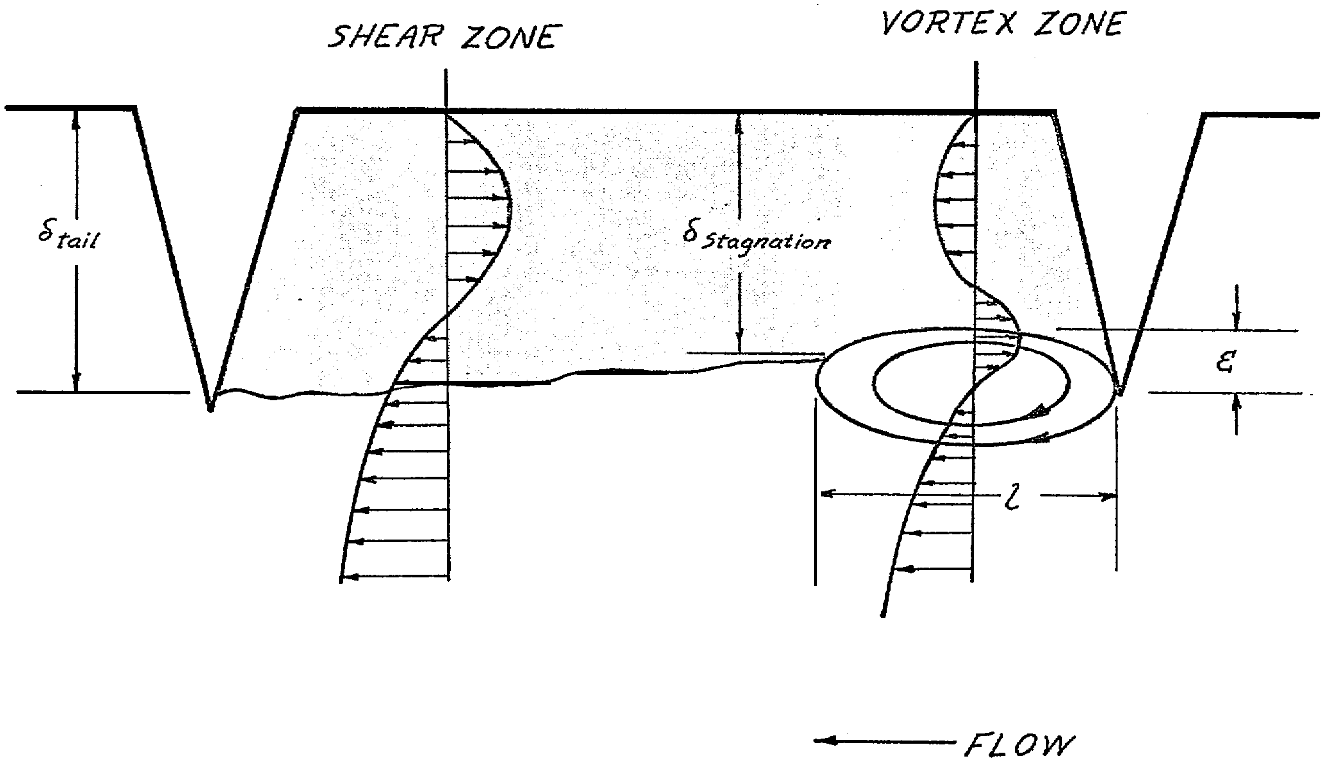
$$V_v{}' = \ell(n - \varepsilon)$$

.FOR A CAVITY, CONTAINMENT IN THE SHEAR ZONE, ALSO VELOCITY DEPENDENT, IS OBTAINED BY EXTENDING A PARABOLIC OIL-WATER INTERFACE FROM THE END OF THE VORTEX ZONE TO AN INTERSECTION WITH THE DOWNSTREAM ROUGHNESS ELEMENT, THE CONTAINED THICKNESS AT THE TAIL IS GIVEN BY:

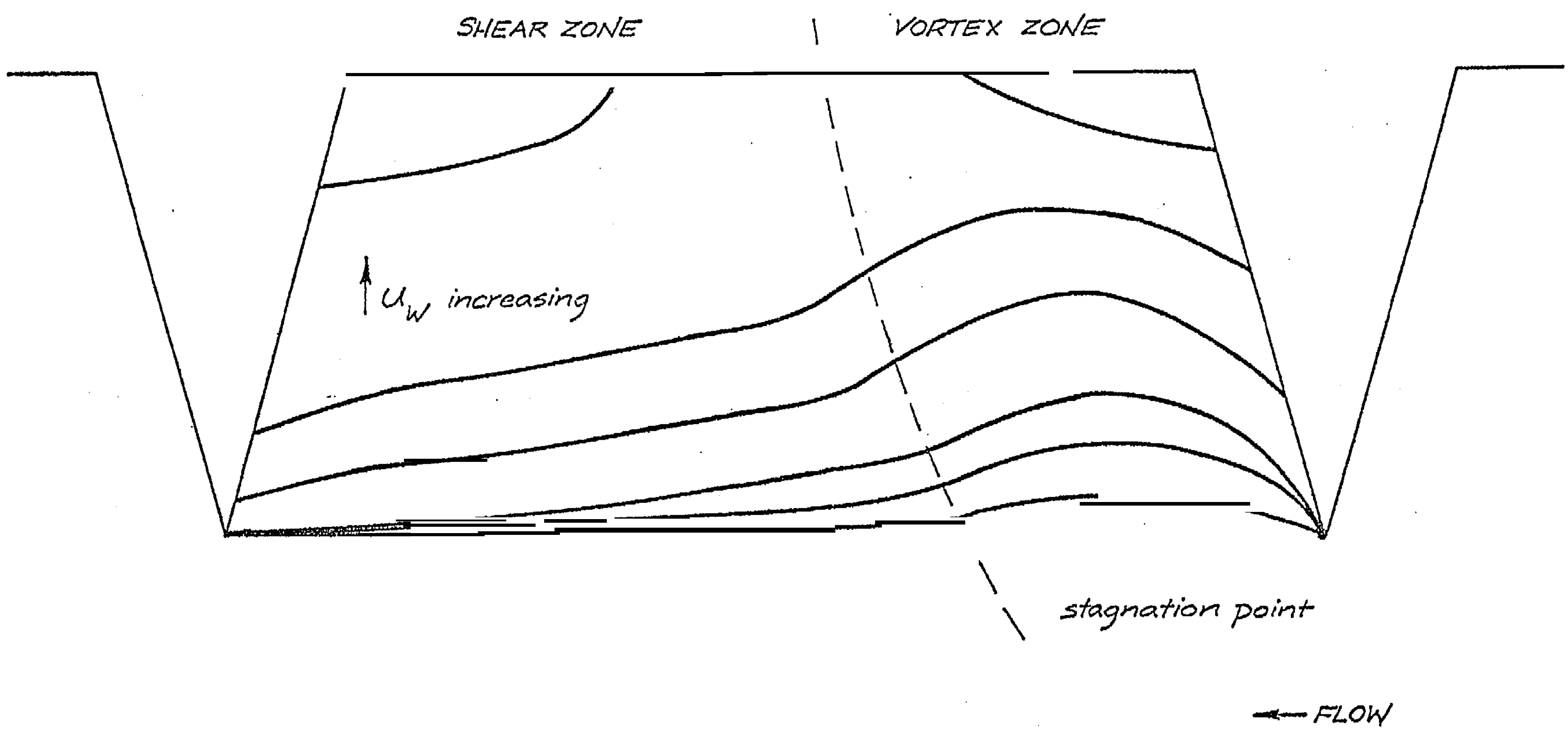
$$\delta_{tail} = \sqrt{\frac{(\lambda - \ell)\, f_s\, U_w^{\,2}}{4\Delta g} + \left(n - \frac{\varepsilon}{2}\right)^2}$$

YIELDING AN APPROXIMATE CONTAINED VOLUME PER UNIT WIDTH IN THE SHEAR ZONE OF:

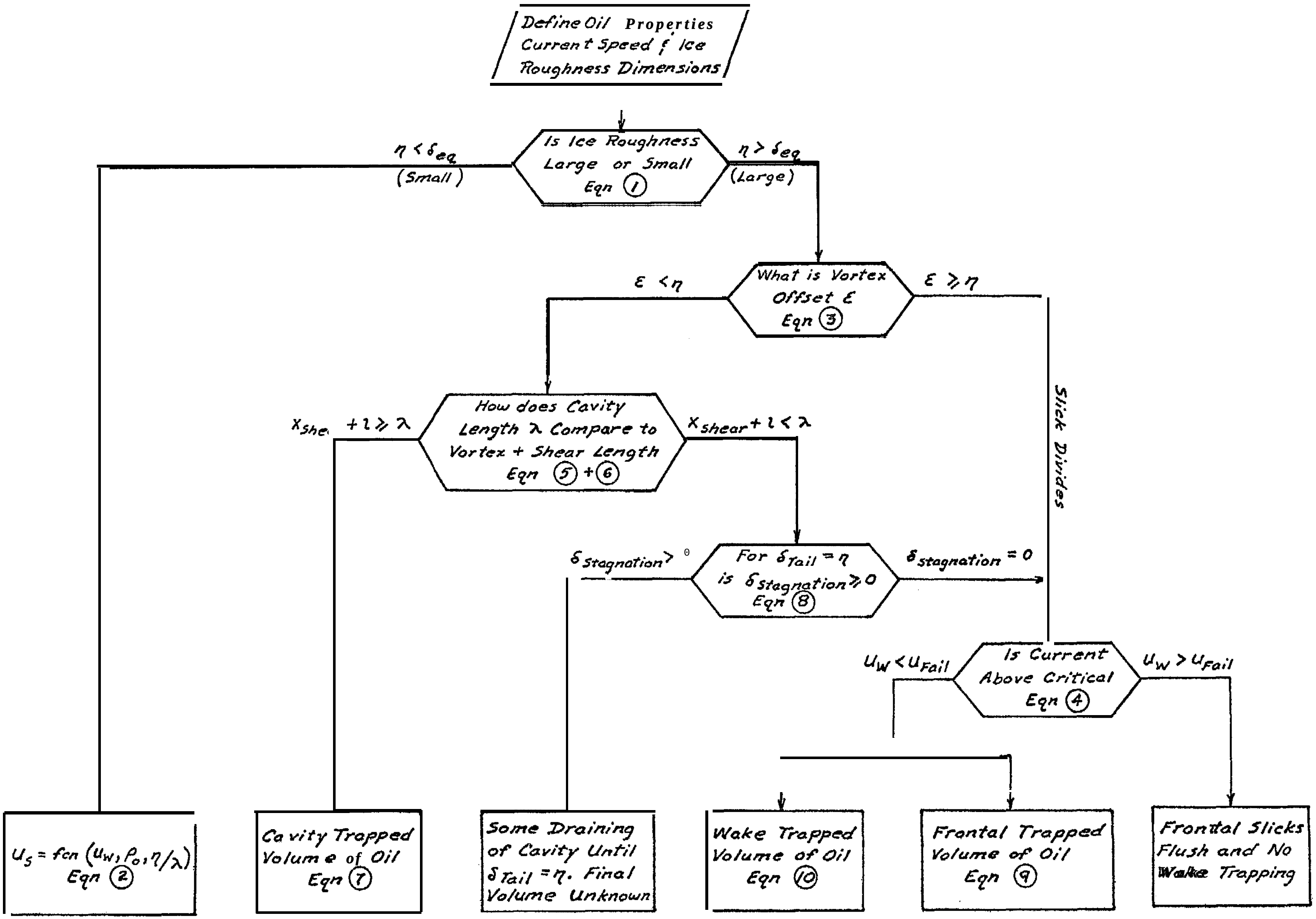
$$V_s' = \frac{\delta_{tail} + \left(n - \frac{\varepsilon}{2}\right)}{2}\,(\lambda - \ell)$$



Generalized Description of Oil Contained in an Ice Roughness Cavity Under the Influence of a Current



Schematic Representation of the Shift in Oil-Water Interface Position Within a Cavity as a Function of Increasing Current


Define Oil Properties
Current Speed & Ice
Roughness Dimensions
Is Ice Roughness
Large or Small
Eqn 1
η < δeq
(Small)
η > δeq
(Large)
What is Vortex
Offset ε
Eqn 3
ε < η
ε ≥ η
Slick Divides
How does Cavity
Length λ Compare to
Vortex + Shear Length
Eqn 5 + 6
Xshear + l ≥ λ
Xshear + l < λ
For δTail = η
is δstagnation ≥ 0
Eqn 8
δstagnation > 0
δstagnation = 0
Is Current
Above Critical
Eqn 4
UW < UFail
UW > UFail
Us = fcn (UW, ρo, η/λ)
Eqn 2
Cavity Trapped
Volume of Oil
Eqn 7
Some Draining
of Cavity Until
δTail = η. Final
Volume Unknown
Wake Trapped
Volume of Oil
Eqn 10
Frontal Trapped
Volume of Oil
Eqn 9
Frontal Slicks
Flush and No
Wake Trapping

Equation 1 $$\delta_{eq} = 1.67 - 8.50\,(\rho_w - \rho_o)$$

Equation 2 $$\left(1 - \frac{U_s}{U_w}\right)^2 = \frac{K}{(0.115F_\delta^2 + 1.105)}$$

Equation 3 $$\varepsilon = \frac{U_w^2}{1.86\Delta g}$$

Equation 4 $$\delta_{tail} = 1.5\left[2\left(\frac{\rho_w + \rho_o}{\rho_w \rho_o}\right)\left(\sigma_{o/w}\, g(\rho_w - \rho_o)\right)^{1/2}\right]^{1/2}$$

Equation 5 $$\iota = 4U_w$$

Equation 6 $$X_{shear} = \frac{4\Delta g}{f_s U_w^2}\left(\eta^2 - \left(\eta - \frac{\varepsilon}{2}\right)^2\right)$$

Equation 7 $$V' = \iota\,(\eta - \varepsilon) + \frac{\delta_{tail} + \left(\eta - \frac{\varepsilon}{2}\right)}{2}\,(\lambda - \iota)$$

where $$\delta_{tail} = \sqrt{\frac{(\lambda - \iota) f_s U_w^2}{4\Delta g} + \left(\eta - \frac{\varepsilon}{2}\right)^2}$$

Equation 8 $$\delta_{stagnation} = \sqrt{\eta^2 - \frac{(\lambda - \iota)\, f_s U_w^2}{4\Delta g}}$$

Equation 9 $$V' = \frac{\left(\eta + \frac{U_w^2}{4\Delta g}\right)}{2}\left(\frac{4\Delta g}{f_s U_w^2}\right)\left(\eta^2 - \frac{w}{4\Delta g}\right)$$

Equation 10 $$V' = 6\, C_D \eta\, \delta_{eq}$$

LIST OF VARIABLES

C_D - roughness form drag coefficient

F_δ - $\dfrac{U_w}{\sqrt{\Delta g \delta}}$

f_s - oil water interracial friction factor

g - gravity constant

K - ice friction amplification factor

U_{fail} - current speed for containment failure

U_s - slick speed

U_w - current speed

V' - approximate volume of trapped oil per unit width

X_{shear} - length of the shear dominated portion of the slick

α - oil-water-ice contact angle

Δ - $\dfrac{\rho_w - \rho_o}{\rho_w}$

δ - local slick thickness

$\delta_{stagnation}$ - thickness of slick in a cavity at the end of the vortex zone

δ_{eq} - equilibrium oil slick thickness

δ_{tail} - thickness of contained slick at the downstream wall

ε - vortex zone offset into a cavity

η - ice roughness height or cavity depth

ι - vortex cell length

λ - cavity length

ρ_o - density of oil

ρ_w - density of water

$\sigma_{o/w}$ - interracial tension between oil and water

VERTICAL MIGRATION

FIRST YEAR ICE

- LIMITED FIELD WORK BY MARTIN AND LABORATORY WORK BY ARCTEC CANADA SUGGESTS THAT OIL TRAPPED BENEATH OR WITHIN FIRST YEAR SEA ICE WILL FLOW TO THE SURFACE AT A RATE OF 0.07 CM/SEC WHEN THE MINIMUM INTERIOR ICE TEMPERATURE INCREASES TO -4°C.

- THEORY PREDICTS THE CRITICAL BRINE CHANNEL DIAMETER FOR INCEPTION OF VERTICAL MIGRATION IS GIVEN BY:

$$d_{\text{Inception}} = \frac{4\sigma}{\delta} \frac{\cos\alpha}{(\rho_w - \rho_o)g}$$

- THEORY PREDICTS THE VERTICAL MIGRATION RATE IS GIVEN BY:

$$\bar{u} = \frac{(\rho_w - \rho_o)g \quad \delta \quad d^2}{32 L \mu_o}$$

MULTI YEAR ICE

- LIMITED STUDIES BY MARTIN AND ENVIRONMENT CANADA INDICATE NO VERTICAL MIGRATION; THE ICE HAS TO MELT DOWN TO THE OIL.

RECOMMENDATIONS FOR FURTHER OIL-ICE INTERACTION RESEARCH FOR BEAUFORT SEA APPLICATIONS

- INVESTIGATE THE CONTAINMENT CHARACTERISTICS OF LARGE FREQUENCY, SMALL AMPLITUDE Sinusoidal ROUGHNESS,
- INVESTIGATE THE EFFECT OF IRREGULAR ROUGHNESS,
- FURTHER DEFINE THE INCEPTION AND RELEASE RATE OF OIL THROUGH VERTICAL MIGRATION FOR BOTH LEVEL AND HUMMOCKED ICE IN TERMS OF OIL PROPERTIES AND ICE CONDITIONS,
- DEFINE CONTAINMENT CAPACITY FOR LONG, DEEP CAVITIES,
- REFINE LENGTH, DEPTH, AND OIL PROPERTY DEPENDENCE OF THE CAVITY VORTEX REGION.
- VERIFY APPLICABILITY OF LABORATORY-BASED SPILL BEHAVIOR PREDICTIONS THROUGH A DEDICATED FIELD TEST PROGRAM OR THROUGH STUDIES OF SPILLS OF OPPORTUNITY,

RECOMMENDATIONS FOR OIL- ICE INTERACTION RESEARCH FOR BERING SEA APPLICATIONS

- INVESTIGATE THE CONTAINMENT AND TRANSPORT OF OIL IN BROKEN ICE FIELDS,
- INVESTIGATE THE BEHAVIOR OF OIL BENEATH ICE AT HIGHER CURRENT VELOCITIES,
- INVESTIGATE THE INTERACTION OF OIL WITH NEWLY FORMING ICE,
- INVESTIGATE THE EFFECT OF ICE EDGES ON THE BEHAVIOR OF SPILLED OIL,